Young SLSNe with ZTF

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Abstract

More than a decade since the discovery of superluminous supernovae, their energy sources and progenitors are still not well understood. The early-time behaviour in particular remains an observational frontier due to the low rates and the challenge of identifying the SLSNe in real-time on the rise. We propose to remedy this with a nightly-cadence ZTF survey in g+r, with the aims of 1) accurately constraining the explosion dates of SLSNe found in ZTF, 2) detect and sample in two filters any light curve "precursor bumps" (suggested to be ubiquitous in SLSNe but currently poorly constrained), and 3) to obtain early-time (¡ two weeks rest frame) spectra of young SLSN candidates, identified by a combination of colors, time since explosion, follow-up UV photometry and host information from PS1 and SDSS. The combination of area and survey speed makes ZTF uniquely capable to carry out such a project.

1 Scientific Motivation

Superluminous supernovae (SLSNe) are a rare class of transients with peak luminosities 10-100 times higher than ordinary core-collapse and Type Ia SNe, and total radiated energies in excess of 10^{51} erg. Such enormous energies cannot be explained by standard supernova models, and the progenitors and explosion mechanisms of SLSNe are still unknown. Suggestions include either a central energy source (such as magnetar spin-down), strong interaction with dense CSM converting kinetic energy to radiation, or the pair-instability explosion of a very massive star.

Since their initial discovery more than a decade ago (Quimby et al., 2007), more than 100 SLSNe have been reported, including ~ 50 found in the combined PTF and iPTF surveys. However, while most of these are well-studied near peak, the early time behavior is often poorly constrained. With its unique capabilities of combining a large survey area with high cadence, ZTF can greatly remedy this deficiency. Specific questions we seek to answer include:

1. Determining the explosion dates and measuring the rise timescales of SLSNe accurately. This is important because rise timescale directly constrains the ejecta mass and thus the progenitor mass. For slowly-declining SLSNe, the rise time is the main discriminator between pair-instability and central-engine models (e.g., Nicholl et al. 2013; Lunnan et al. 2016).
2. Some hydrogen-poor SLSNe (SLSN-I) show a precursor "bump" on the rise, with typical timescales of $\sim$ 10 days (Leloudas et al., 2012; Nicholl et al., 2015; Smith et al., 2016; Vreeswijk et al., 2017). It has been suggested that this feature is ubiquitous (Nicholl & Smartt, 2016), but the presence of such a bump is poorly constrained due to a lack of well-sampled early time data in the majority of SLSNe. Both finding more SLSNe with such an early-time feature, and constraining how common this feature is, will be of great value. Performing the search in two filters (e.g., g and r) so that color information during the bump would also be available would increase the scientific utility significantly.
3. Optical spectral features of SLSNe at very early times are completely unknown. As demonstrated by flash spectroscopy of core collapse SNe IIP (Gal-Yam et al., 2014), early spectroscopy of SLSNe may identify variable spectral features which probe the stellar envelope and/or circumstellar medium surrounding the progenitor stars. No spectra have been obtained during the initial precursor bump to date. For this project, any spectra taken before the rising to the primary peak would bring new discoveries. From Figure 1, the "young SLSNe" would be referring to any time before 20 days of explosion. Here this time interval is in rest-frame. At $z \sim 0.3$, the observed time scale could be as long as 26 days.

The aims of the first two projects are to measure the early-time photometric properties of SLSNe. For these two projects, spectroscopic classifications are required, but need not be done on a rapid timescale. Since SLSNe rise on slower timescales than other SNe (30-50 days), one can use the light curve morphology and rise time (together with host photometric redshift) to select candidates, and classifications can thus be done near peak. We stress that the utilities of the light curves, particularly for the second project, is greatly increased by performing the search in two filters so colors are available even if the object is classified at a later time.

The third project, however, does require rapid spectroscopic follow-up, on the timescales of 20 days. We describe our proposed strategy for selecting candidates for follow-up in Section 1.3.

1.1 Competitiveness of ZTF

ZTF is required to address these questions because SLSNe are very rare, with crude rate estimates of 200 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ at $z \sim 0.16$ (Quimby et al., 2013). (Section 1.4 discusses the expected numbers for different survey parameters.)

(i)PTF has found many SLSNe, but lacks early-time data in most cases. This can be understood by that the area covered by (i)PTF is by necessity much smaller, and fields were rarely followed for more than 2-3 months at a time particularly during iPTF. The long time scales of SLSNe (several months) increases their overall detection rate, but also makes it more likely to discover objects already at peak or declining as you switch to a new field.

1.2 Figures of Merit

The first two projects are evaluated on the basis of the number of objects eventually classified as SLSNe where (1) the SLSN is discovered on the rise, and we can constrain the explosion epoch to within a few days, and (2) we either detect, or rule out, the presence of a precursor bump.

The third project would be deemed successful if we manage to obtain a spectrum of a SLSN taken within a rest-frame 20 days of explosion.

1.3 Real time discovery – Selecting Young SLSNe candidates

As described above, the third project – early-time spectroscopy of young SLSNe – requires to select young SLSN candidates for spectroscopy. This project does require human scanners, but not on the very rapid turnaround timescale of other “early SN” projects. To pick out young SLSNe, we propose the following selection criteria:

1. blue color with $(g - r) < -0.3$ (AB mag): For both young SLSNe-I and SLSNe-II, we require very blue $(g - r)$ colors, as we expect the photospheric temperatures to be very hot during these earliest phases. This also holds for during the precursor bump: Figure 1 shows the light curve of the SLSN-I DES14X3taz, the *only* SLSN published to date with color information during the precursor bump, showing temperatures in the range of 20,000-30,000 K. A temperature of 20,000 K at a redshift $z = 0.15$ corresponds to an observed color $g - r = -0.3$ mag, motivating the cutoff.

   Before triggering spectroscopy, we will also confirm blue SED by triggering Swift and SEDmachine for UV photometry. Since we are aiming for a spectrum within the first two weeks since explosion, extremely rapid turnaround is not needed and waiting for UV confirmation is acceptable.

2. Previous observations showing that the object in question is younger than rest-frame 20 days from the explosion date.

3. photometric redshift $z_{phot} < 0.3$. We can use PS1 photometric redshifts to restrict young SLSN candidates for spectroscopy at low redshifts. We will also use available catalog data as well as any past variability to rule out the likelihood of an AGN (e.g. WISE colors, SDSS colors, X-ray or radio source). As the host galaxies of SLSN-I are typically low-mass

dwarf galaxies (Lunnan et al., 2014), AGN contaminants are much easier to rule out than in the case of e.g. tidal disruption events.

The number of expected contaminants can be estimated from the iPTF g+R experiment conducted in 2016. Unfortunately, the analysis of the data is not complete by the time of the white paper deadline; our proposed selection criteria and in particular color cut may evolve as a result. However, we note that contaminants that meet these criteria but turn out not to be SLSNe are likely to be very young SNe of other types or tidal disruption events, and also of interest to other groups in the ZTF collaboration.

1.4 Expected number of candidates:

As described below, we propose a ZTF survey with a 1-day cadence for 1 year, covering 10,000 sq. degrees every night.

At $z \sim 0.16$, this area corresponds to a co-moving volume of $0.33\,\mathrm{Gpc}^3$ with $\mathrm{H}_0 = 69.8, \Omega_\mathrm{M} = 0.286, \Omega_\mathrm{vac} = 0.714$. Thus the total number of SLSNe with this 1 year ZTF survey is 66. Many of these 60 SLSNe would not be young. Below is how we estimate the fraction of young SLSNe (less than rest-frame 20 days after explosions). Let us assume that the discovered SLSNe have equal probabilities of being young, near peak and old, and let us assume the total time scale of a SLSN LC is 200 days (rest), we should have a probability of 20/200 =10% finding our young SLSN candidates.

So assuming 10% of the total sample of SLSNe will be at phases earlier than rest-frame 20 days, we expect 7 young SLSNe in this 1 year survey.

2 Proposed Observations

We propose the following ZTF observation for 1 year:

1. A one-day cadence search (i.e., single observation in each g and r nightly). This would allow us to cover an area of $\sim 11,000$ square degrees, according to the assumptions in the call for proposals (3760 sq degrees/hr in a single filter; average 6 hrs/night).
2. use two filters, g and r. $(g-r)$ colors will allow us to make efficient selections of young SLSN candidates, that we will further follow up with UV photometry before triggering spectroscopy. Also for candidates that are classified near peak, having colors on the rise and particularly during a precursor bump are valuable for studying the early-time behavior.

The primary reasons for 1-day cadence are (1) the precursor bumps that have been observed in SLSNe so far have typical duration of $\sim$ 10 days. Figure 1 illustrates an example from DES14X3taz, a SLSN-I at z=0.608. Time scale for photometric variations at the first minimum between the first and the primary peak is on the order of a few days. (2) For accurate measurements of explosion dates, it is important to have deep early detections and limits. With a 1-day cadence, we can co-add individual images to obtain deep photometry at early phases.

2.1 Sensitivity to survey parameters

The first two science goals are not particularly sensitive to changes in cadence and filter choices, as long as it is faster than the proposed 3-day MSIP cadence. A single-filter search would hurt our capability to pick out SLSNe at early times, since the color information is crucial. A faster than one day cadence will cut down the area surveyed correspondingly, and with it our probability of detecting one of these rare events.

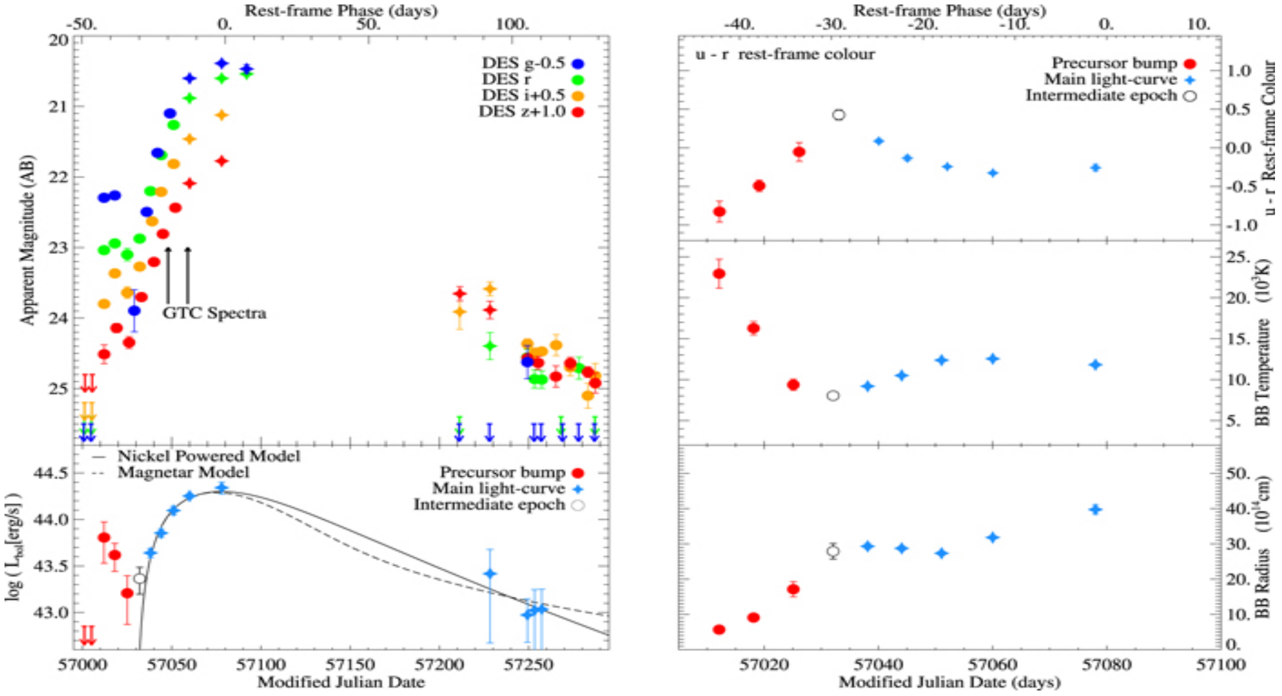

Figure 1: The monochromatic and bolometric light curves of SLSN-I DES14X3taz. This figure is adopted from (Smith et al., 2016). The evolution trend of $(u-r)$ (rest-frame) color and blackbody temperature as a function of time are illustrative for our selection criteria of young SLSN candidates.

3 Supporting Observations

3.1 Photometric follow-up

For young SLSN candidates, we will trigger Swift photometric follow-up observations; UV photometry is critical for this program. For SLSNe near their peak brightness, additional photometric follow-up in other optical filters can be obtained with LCOGT and other smaller telescopes which are partners of GROWTH program. These data would be useful for calculating bolometric light curves.

3.2 Use of other telescopes

Because young SLSN candidates are so rare and very faint, it is not possible to use other small telescopes to supplement a ZTF survey with a long cadence. The large area that can be covered by ZTF is critical.

3.3 Follow-up spectroscopy

All three projects need spectroscopic classifications. However, the spectral classifications for the first two projects can be done near peak, thus, DBSP on P200 inch is sufficiently sensitive to get good spectra as shown by our experience with PTF SLSNe. Lin Yan will have access to this resource.

For the third project, the immediate spectroscopy needs to be obtained when SLSNe are young and (comparatively) faint. We will need spectrographs on 10-meter class telescopes. Caltech Keck resources will contribute a small number of these classifications. We will write Gemini-N ToO proposals.

3.4 Other external resources

We will put in large observing programs to Swift to obtain both UV and radio observations of young SLSN candidates. Swift UV photometry will allow us to measure photospheric temperature properly.

4 Expertise to Undertake Project

All of our team members have substantial experience in the area of SLSN research.

5 Manpower and Timeline

The project will be co-led by Lin Yan and Ragnhild Lunnan, and with participation from Ofek, Gal-Yam and Yaron from Weizmann from the ZTF partnership. Two additional science collaborators include Dan Perley and Robert Quimby. We will submit a formal request to the ZTF board to obtain approvals for Perley and Quimby as science collaborators for this project. Both Perley and Quimby can bring in telescope observing resources as well as manpower. Each of the three main science areas described are expected to lead to papers. Between Yan and Lunnan, the work is manageable.

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